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Testing of a hybrid membrane system for groundwater desalination in an Australian national park

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The results of a field trial desalinating brackish bore water in an Australian remote National Park site are reported in this paper. Two membranes, operated with varying operation pressures, were tested with regards to flux, recovery, retention, power and specific energy consumption. The aim of such a performance evaluation is the determination of a safe operating window when the system is driven with solar energy and hence a variable power source. Submerged ultrafiltration was effective in reducing high feedwater turbidity of up to 370 NTU. For the system, designed for a production of about 1000 L/d for remote communities, the specific energy consumption (SEC) was below 5 W.h/L when operated at a pressure above 7 bar. Retention of multivalent ions was stable at > 98% while the retention of monovalent ions varied between 88 and 95% depending on system pressure with a maximum between 7 and 10 bar.

Keywords: Brackish water, nanofiltration, renewable energy, solar energy, photovoltaic, reverse osmosis, small community, specific energy consumption.

1 Introduction

Water availability and quality are a major problem in many Australian remote locations such as national parks. In national parks, for example, peak demands cannot be met during holiday periods and water has to be brought by trucks when stored resources are depleted at considerable cost. To address such problems of small and remote locations a desalination system using hybrid membrane technology – submerged ultrafiltration (UF) and nanofiltration (NF)/reverse osmosis (RO) – was developed [1]. The capacity of the system is about 1000 L/d. Reverse osmosis is known to require relatively high operating pressures and hence a substantial amount of energy, which results in high greenhouse emissions. Furthermore, electricity is often not available in remote locations and hence the reduced energy requirements enable the system to run be powered from solar energy.

While quite a number of reverse osmosis units driven by renewable energy have been developed for seawater desalination, only few photovoltaic (PV)-powered membrane filtration units have been designed to treat brackish water (see Table 1). The majority of these systems were designed to operate at relatively low pressures, 4 to 16 bar, and the salt retention (where data is available) of all systems was greater than 90%. Three of the systems (Mexico, Oman and Israel) were designed for 24 hour operation and include a large bank of batteries that provides power during cloudy periods or at night. However, the presence of batteries is not ideal due to: i) the additional electrical losses and reduced system efficiency; ii) increased

system maintenance; iii) use of strong chemicals and the risk of spillage; and, iv) the problems associated with battery recycling in developing countries.

It is difficult to compare the specific energy consumption (SEC) of the systems due to the wide range in feedwater salinities (as total dissolved solids (TDS) contents), however it can be said that the system in Portugal was a very small and early prototype, which would result in a higher SEC. Recovery strongly depends on the applied system pressure and has strong implications on the SEC.

Table 1 Overview of existing PV-powered membrane filtration units designed to treat brackish water.

| Location | TDS (g/L) | Pressure (bar) | Salt Retention (%) | Recovery (%) | Clean Water (m ³ /d) | PV Array (kW _p) | Battery | SEC (kWh/m ³) | Reference |
|-----------|--------------------------------|-------------------|--------------------------|-----------------|---------------------------------------|-----------------------------------|---------|------------------------------|-----------|
| Portugal | Conductivity 2 – 5 mS/cm | 4 | 90 | 2 | 0.02 | 0.15 | No | 25.6 | [3] |
| Australia | 5 | — | — | 16 or 25 | 0.4 | 0.12 | No | — | [4] |
| Australia | 3.5 | 4 – 10 | 92 | 10 | 0.1 | 0.26 | No | 8 | [1] |
| Mexico | Brackish (1.5-5) | 40 | — | — | 0.7 – 1.4 | 2.5 | Yes | 4.0 – 6.9 | [5, 6] |
| Oman | 1 | 12 | 96.6 | 65 – 70 | 5 | 3.25 | Yes | 2.3 | [7] |
| Israel | 4 | 14 – 16 | 98 | 50 | 3 | 3.5 | Yes | — | [8] |

System is equipped with inverter(s) and AC pump(s).

Many existing desalination systems neglect the issue of membrane fouling. Fouling of reverse osmosis membranes is caused by organic matter, inorganic salt precipitation, colloidal or particulate deposits and in the longer term by microorganisms growing in the system and on the membranes [2]. Thorough pretreatment can prevent or delay such fouling. For this reason a hybrid UF-NF/RO system was designed, where UF retains colloids, particulates, bacteria and some organic matter and hence prevents the deposition of those materials on the NF/RO membranes. Further fouling caused by organic deposition and salt precipitation can be prevented by correct operation of the system. While this is relatively simple when power is sourced from a continuous source such as the electricity grid, with a variable power source such as solar energy, this is more difficult as flow and pressure are likely to vary significantly.

In this study the results of a field trial with the third system prototype were conducted at an Australian National Park. While the system was operated with a constant power source, the pressure was varied to investigate the variation of performance of the system with the aim to determine a suitable operating window.

2 Materials and Methods

2.1 Depot Beach Water Situation

The water treated was the groundwater supply at Depot Beach camping ground and cabins within Murrumbidgee National Park, located on Australia's south-east coastline north of Bateman's Bay. The water was both brackish and turbid (210 – 370 NTU) and is normally used for fighting fires and non-potable usage such as showering and toilet flushing. Drinking water is provided from rainwater storage. The water demand fluctuates significantly with an average of 1000 L/d, a maximum of 16000 L/d over the summer holiday period and a minimum

of 680 L/d in winter from June to August. For example, in the summer of 2002 – 2003 severe drought meant that all rainwater supplies were depleted and water was being trucked in several times per day. The cost for such truck delivered water is A\$11-45/m³ (compared to tap water cost of A\$1/m³) depending on truck capacity and distance travelled. Hence the National Park management is interested in treating the available bore water to supplement rainwater. Naturally, a system like the Reverse Osmosis Solar Installation (ROSI) described here, would provide a much more environmentally, socially – and perhaps even economically – sustainable solution.

2.2 Water Quality

The results of the feed water analysis are presented in Table 2. The bore has a history of high aluminium, iron and manganese concentrations. Combined with high salinity, high turbidity and dissolved oxygen values, undesirable taste and odour the water is not considered a health risk, but rather an aesthetic problem. As can be seen in Table 2 a number of water quality parameters exceed drinking water guidelines. In particular the salt composition indicates a brackish nature of the bore water (total dissolved solids 1.5 – 5 g/L) and hence the need for desalination.

Table 2 Water quality of Depot Beach bore sampled during field trials (4/9/04) and comparison with Australian Drinking Water Guidelines 1996 (August 2000 update) [9].

| Parameter | Symbol | Molar Mass (g/mol) | Unit | Sample Value | Guideline Value |
|-----------------------|------------------------------------|--------------------|-------------|--------------|--------------------------|
| Arsenic | As | 75 | mg/L | <0.005 | 0.007 |
| Boron | B | 11 | mg/L | 0.21 | 0.3 |
| Calcium | Ca | 40 | mg/L | 142.1 | (see CaCO ₃) |
| Chloride | Cl | 36 | mg/L | 1843 | 250 |
| Fluoride | F | 19 | mg/L | <0.10 | 1.5 |
| Iron | Fe | 56 | mg/L | 28.87 | 0.3 |
| Magnesium | Mg | 24 | mg/L | 192.0 | – |
| Manganese | Mn | 55 | mg/L | 0.50 | 0.5 |
| Nitrate | NO ₃ ⁻ | 62 | mg/L | <1.0 | 50 |
| Nitrite | NO ₂ ⁻ | 46 | mg/L | <0.1 | 3 |
| Potassium | K | 39 | mg/L | 19.2 | – |
| Sodium | Na | 23 | mg/L | 1125 | 180 |
| Sulphate | SO₄²⁻ | 96 | mg/L | 340 | 250 |
| Total Hardness | CaCO₃ | 100 | mg/L | 1146 | 200 |
| pH | - | - | - | 6.7 | 6.5 – 8.5 |
| Conductivity | - | - | mS/cm | 6.35 | – |
| Turbidity | - | - | NTU | 370 | 5 |

2.3 Reverse Osmosis Solar Installation (ROSI)

The reverse osmosis solar installation (see Figure 1A) is operated during this field trial with a constant power source. The treatment system consists of six Zenon Zeeweed ZW10 modules connected and submerged in an aerated 200 litre tank to form the pre-treatment system, as shown in Figure 1B. A gentle suction (about 0.5 bar) is applied to draw permeate through the hollow fibres, which have a nominal pore size of 0.04 µm. Subsequently two different membranes were tested, the Filmtec NF90 and BW30 4" spiral wound elements. The pump

was a Mono Pumps LowFlow LF 502, was capable of high pressures (up to 24 bar) and delivered a maximum flow of 470 L/h at a pressure of 15 bar.

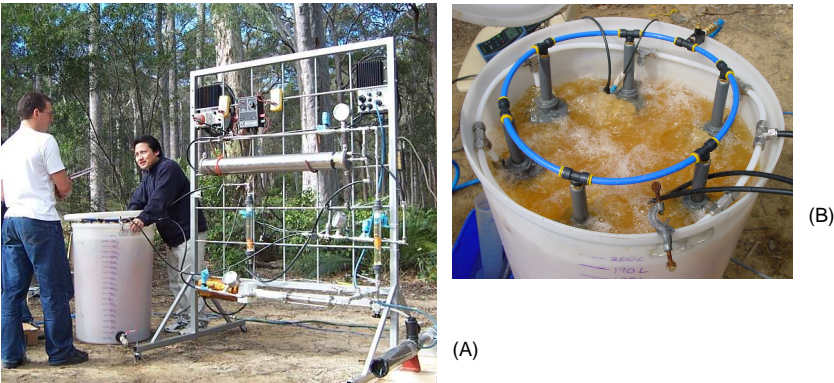


Figure 1 Picture of (A) Reverse osmosis solar installation at Depot Beach and (B) ultrafiltration pre-treatment in the aerated feed tank.

2.4 Experimental

During the four day field trial a number of experiments were performed. In this paper, the results of experiments conducted at varying pressure are presented. During these experiments, power was supplied by a 240V_{AC} line, which was connected to an AC interface that converted the power to 180V_{DC}. This simulates the performance of system as if solar panels were connected, with the solar motor controller regulating the performance of the pump. The AC interface is normally used as a backup power supply, when solar energy availability is low, however to understand the results of these initial experiments it was desirable to keep pressure and flow constant. For later experiments where solar energy will be used, the varying current from the PV modules will result (primarily) in a change in flow out of the LF502 pump.

Pressure was controlled via the outlet valve at the spiral wound membrane module. The pressure was varied from 4 to 15 bar in 1 bar increments at constant feed flow, which naturally results in a increase in recovery and power consumption. Samples were collected at each interval from the feed tank, UF permeate, NF/RO permeate and NF/RO concentrate. Turbidity, pH, temperature, and conductivity were measured immediately, while 25 mL of sample was collected for later elemental analysis. Permeate flux, voltage and current were also measured. Both permeate and concentrate were recirculated into the feed tank.

2.5 Analytical Methods

Anions were analysed using ion chromatography (IC) and cations using inductively coupled plasma atomic emission spectroscopy (ICP-AES) and results were confirmed with inductively coupled plasma mass spectrometry (ICP-MS) to eliminate interference. All samples were analysed by NSW Health. Analytes by IC are chloride, fluoride, nitrate, nitrite and sulfate. A Dionex CS90 Ion Chromatograph fitted with a 20cm x 4mm column filled with AS14-A, 5

micron size ion exchange resin was used. The eluent was 8 mM Na_2CO_3 and 1mM NaHCO_3 . The detection was by conductivity after a chemical suppression cell. Analytes by AES were As, B, Ca, Fe, Mg, Mn, K, Na. The MS was used only to confirm As when the As result by AES was interfered with by the presence of other constituents. The same acidified sample was used in both techniques.

3 Results and Discussion

The main performance indicators of a small desalination system are productivity in the form of flux and recovery, desalination efficiency in the form of retention with regards to total dissolved solids, conductivity or individual elements, and energy requirements in the form of power or specific energy consumption.

3.1 Ultrafiltration Performance

Ultrafiltration (UF) retains colloidal and particulate matter. In this application UF is required to reduce the high turbidity of the source water to protect the NF/RO membranes. The turbidity of the UF permeate was consistently below detection limit. Further, the retention of manganese was in the range of 62 – 95% and the retention of iron >99.9% indicating that those compounds were primarily present in solid form. A deposit of reddish particulates on the UF membranes was observed and controlled with an air compressor used for bubble generation.

3.2 Flux and Recovery

Seeing that pressure is the driving force for water permeation, flux increases linearly with increasing pressure (see Figure 2). The flux of the NF90 membrane is about 30% higher than that of the BW30 membrane. Seeing that the feed flow is constant, recovery is proportional to flux and values vary between 5 and 70%. This is a significant variation, but could be a realistic scenario when operated with a varying power source. The implications of this variation are that retention could be affected substantially.

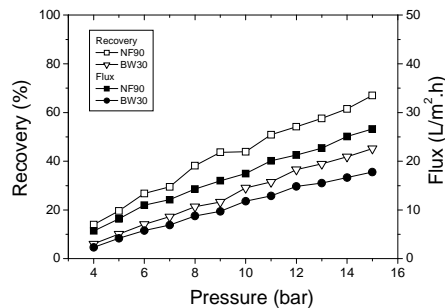


Figure 2 Flux and recovery for BW30 and NF90 membranes as a function of applied pressure.

3.3 Retention

Conductivity values of concentrate and permeate streams are shown in Figure 3 together with retention of conductivity. Retention is larger than 90% for both membranes, and in the case of the BW30 membrane increases with pressure. This behaviour is expected for reverse osmosis

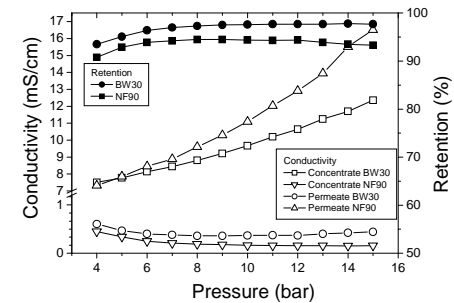


Figure 3 Permeate and concentrate conductivity and retention for BW30 and NF90 membranes as a function of pressure.

and can be explained with reduced diffusion as flux increases. In the case of the NF90 membrane retention also increases with pressure, but retention decreases above 12 bar. This decrease is not desirable and is an effect of high flux and recovery, resulting in low crossflow velocity and substantial concentration polarisation which causes an increase of diffusion. The difference between the two membranes is due to their different permeabilities.

A similar trend is observed when an elemental analysis of the samples is taken as shown in Figure 4 and Figure 5 for the NF90 and BW30 membranes, respectively. While the data for the BW30 is more scattered, in the case of the NF90 membrane two distinctive retention patterns are observed. Firstly, hardness (as CaCO_3) and the multivalent ions sulphate, manganese, magnesium and calcium are retained at >98% and retention is independent of pressure. Secondly, the monovalent ion retention is consistently lower and reflects the pattern that was observed with conductivity. Retention increases by 5 – 7% from 4 to 7 bar and decreases by about 3 – 4% at pressures from 10 to 15 bar. While the overall values are similar for both membranes, the distinction is clearer for the NF90 membrane, which could be due to the fact that this membrane is a nanofiltration membrane and hence is expected to be selective between mono- and multivalent ions. It is somewhat surprising, however, that the retention of both membranes is very similar given the substantially different permeability.

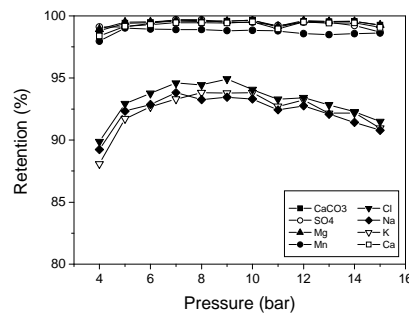


Figure 4 Retention of selected ions as a function of pressure for NF90 membrane.

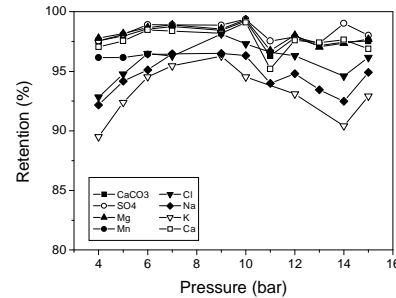


Figure 5 Retention of selected ions as a function of pressure for BW30 membrane.

3.4 Power and Specific Energy Consumption

Power requirements increase linearly with increasing pressure and are independent of the membrane for a given pressure. The amount of water produced at a certain pressure is reflected in permeate flow (or flux) and hence strongly membrane dependent. Seeing that the amount of permeate produced increases significantly at higher pressure, the specific energy consumption (SEC) decreases with pressure.

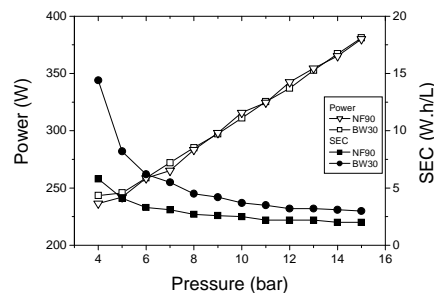


Figure 6 Power and specific energy consumption as a function of pressure.

In comparison with the performance of other systems reported in Table 1 this system performs well with SECs below 5 W.h/L at pressures above 7 bar. The ability of the pump to maintain high flow at high pressures results in a consistently decreasing SEC, while in the previous prototype the pump limitation resulted in a minimum of the SEC at 5.5 – 7 bar [10].

4 Conclusions

Pressure strongly influences the performance of nanofiltration/reverse osmosis systems. Flux and recovery increase with pressure and determine the overall volume of clean water that can

be produced in a day. Hence the amount of water produced is directly dependent on the solar insolation. This has implications on water quality. At low pressures (or energy levels) the flux is low and diffusion of contaminants (such as salt) high which results in high product water salinity. At very high pressures recovery for the membrane with higher permeability is such that feed side salt concentrations increase substantially and also cause diffusion of contaminants. Hence the operating window for a higher flux membrane may be somewhat smaller than for the low flux membrane. The specific energy consumption (SEC) is very competitive for this system with values of 3.0 – 5.5 and 2.0 – 3.1 at pressure of 7 to 15 bar for the BW30 and NF90 membranes, respectively.

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